The Electric Dipole Moment of the Neutron

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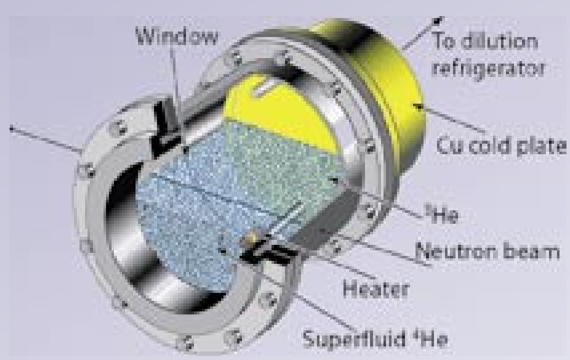
We have a general notion of the meaning of the term "symmetry" particularly in regard to art and biology. In biological systems, symmetry at the molecular level has been known since 1848 when Pasteur discovered that tartaric acid could exist in two forms (e.g., "left-handed" and "right-handed," referred to as stereoisomers) that are mirror images of each other. Both forms are produced in inorganic processes, whereas only one-handedness is produced by or is useful to natural organic processes. The very fact that molecules can exist with either handedness implies that the atomic constituents are themselves very highly symmetric. This is expected because the electrostatic interaction that binds electrons in atoms does not distinguish between left and right.

In 1949, Norman Ramsey and Ed Purcell questioned the character of the nuclear force, in particular, whether it "conserved parity symmetry," P, which is to ask whether the force is the same if viewed as a mirror image (e.g., if left and right are important). They concluded that lack of P conservation would imply the possible existence of an EDM of the neutron. Shortly after, P asymmetry was observed in radioactive decay and subsequent theoretical work showed that a neutron EDM (nEDM) would require the existence of time reversal (T) asymmetry in addition to P asymmetry. As in the case of the question of P symmetry, in our daily lives we know that just as there is a distinction between left and right, there is a distinction between time moving forward and backward. If we drop a glass object on the floor and see it shatter, we do not expect to see the pieces subsequently come back together and the



(a)
(b)
(c)
(d)

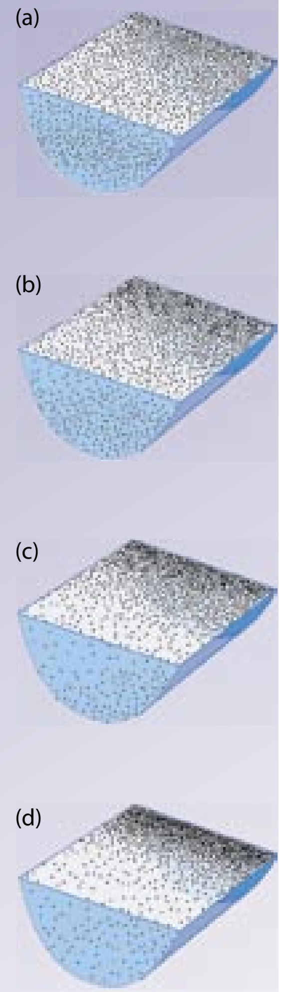


Figure 1. A three-dimensional rendering of the apparatus used to measure the diffusion and distribution of ^{3}He (dots) in superfluid ^{4}He (blue liquid in the bottom half of the cryostat cylinder). The window at the near end of the cylindrical cryostat is normally covered by a PMT, which is used to detect the scintillation light. The neutron beam enters from the right. The horizontal cryostat is mounted on a motion-controlled frame that allows it to be moved in two dimensions transverse to the beam. The effects of increasing heater power on the ^{3}He distribution in the cell are shown in the panels along the right side [Figure 1(a) through (d)]. In each case, the ^{3}He (dots) rapidly migrates away from the heater and towards the end of the cryostat connected to the dilution refrigerator. Figure 1(a) through (d) shows that the migration becomes more pronounced as the heater is set to 1, 2, 3, and 10 (arbitrary) heat units, respectively.

object jump back into our hand. However, nothing in the microscopic interactions that describe the object, its falling, and its subsequent shattering precludes this possibility. In this case, the direction of time we perceive is because such odd behavior is so improbable as to be impossible. As of 1964, it was assumed that the fundamental interactions governing the microscopic behavior of matter were time-reversal symmetric and that the flow of time in the universe was due to statistics as in the case of the shattering glass.

In 1964, T asymmetry, in addition to P asymmetry, in a fundamental interaction was (indirectly) observed in the decay of the "strange" K_0 meson. This again opened the possibility of an nEDM, and experimental limits on the possible size of the nEDM have been crucial in establishing the veracity of theories put forward to explain K_0 decay. The continuously improving nEDM experiments, with sensitivity increased by 9 orders of magnitude since 1950, have ruled out more theories than any other set of experiments in the history of physics. At the present level of EDM experiments, theoretical extensions to the so-called Standard Model, such as "supersymmetry," are being stringently tested.

The nEDM

A neutron has three quarks, a net charge of zero, and a magnetic moment. An nEDM would be evidence that the charge distribution of the internal quark constituents of the neutron is displaced relative to the center of mass. This displacement must lie along the neutron spin along with the magnetic moment.[1]

The usual technique employed for measuring the nEDM is magnetic resonance. When a polarized neutron is placed in parallel electric and magnetic fields, the spin precesses at the Larmor frequency (modified by the electric-field term)

$$f = \gamma B \pm 2dE, \qquad (1)$$

where γ = 3 Hz/mG (milli-Gauss) is the neutron gyromagnetic ratio, B is the applied magnetic field (typically, 10 mG or less), d is the nEDM usually expressed in "electron-centimeters" ($e$cm), and E is the applied electric field (typically 10 kV/cm)—the factor two in the second term results from the fundamental definition of the EDM. Under T reversal, the sign of B changes relative to E. We can produce this reversal in the laboratory by reversing E; a change in precession frequency with this reversal would be a direct detection of T asymmetry. The figure of merit, F, for an nEDM experiment is

$$F = E\sqrt{N\tau}, \qquad (2)$$

where E is the applied electric field, N is the number of neutrons measured per measurement cycle, and τ is the coherence time of the spin precession. The present best limit for the nEDM results from an experiment that employs spin-polarized UCNs stored for about 100 s in a 10 kV/cm electric field.[2]

UCNs are neutrons with kinetic energy so low they can be reflected from material surfaces for all angles of incidence. The energy of a UCN ($< 300 \times 10^{-9}$ eV) corresponds to a velocity of less than 7 m/s (just about the speed required for a four-minute mile!) and an effective temperature of 0.005 K.[3] UCNs can be stored in "bottles" for times approaching the β-decay lifetime of the neutron (~ 900 s).

Because the neutron precession frequency depends on the value of the magnetic field (see Equation 1), a spurious magnetic field associated with application of the electric field (caused by leakage currents, for example) can create a "false" or systematic EDM signal. To account for this possibility, the most recent experiment employs a "co-magnetometer" based on a dilute spin-polarized ^{199}Hg gas that fills the UCN storage vessel and is detected optically.

The results of this work limit the nEDM to $d < 5 \times 10^{-26}$ $e$cm. To understand the smallness of this limit, if the neutron were enlarged to the size of the earth, the displacement of the charge would correspond to about one wavelength of visible light.

An nEDM Experiment in Superfluid ^{4}He

For the experiment described in Reference 2, the UCN density was limited to 50/cm^3. More effective "superthermal processes" of producing UCNs are now under study at LANL.[4] In a superthermal source, relatively high-energy neutrons with an effective temperature of 10 K to 100 K (as a result of conventional moderation) inelastically scatter to lower energy in a material and become UCNs. If the scattering material is in a UCN storage bottle, the UCNs are trapped (the incoming high-energy neutrons easily penetrate the bottle). If the scattering material is at a very low temperature, the inverse process of inelastic scattering to high energy is impossible. Furthermore, if the material has low neutron absorption, the density of UCN builds up until the rate of production equals the rate of loss due to β-decay and unavoidable losses on the storage-bottle surfaces. Two effective superthermal converters are superfluid ^{4}He and solidified deuterium gas. Superfluid ^{4}He is a nearly perfect superthermal converter because it has no nuclear absorption. We anticipate that we can obtain a UCN density of over 500/cm^3; we demonstrated the basic technology at the LANSCE in December 2001. We are proposing a new type of nEDM experiment based on this technology[1,5] and expect a possible factor of 100 improvement in the experimental limit, because we anticipate

- a factor of 5 increase in the electric field because of the good dielectric properties of superfluid helium,
- a factor of 100 increase in the number of stored UCNs, and
- a factor of 5 increase in the spin coherence time.

Using Equation 2 above, this implies a factor of about a 100 increase in the figure of merit.

^{3}He Magnetometry

The only substance that can dissolve and remain in solution in superfluid ^{4}He at low temperatures is the rare isotope ^{3}He. ^{3}He has an intrinsic nuclear spin of one-half and a magnetic moment. Furthermore, it is expected to have an extremely small EDM because of shielding by the atomic electrons. ^{3}He can be polarized and dissolved in superfluid ^{4}He, and we are presently studying the possibility of using it for a co-magnetometer in a superfluid ^{4}He nEDM experiment.

It is well-known that ^{3}He absorbs neutrons readily, with the reaction yielding a proton, a triton, and 764 keV of kinetic energy. The energy released by this reaction creates scintillation light in superfluid helium, and the fact that such a reaction occurred can be readily detected. Furthermore, the reaction is spin-dependent; when the ^{3}He and UCN spins are parallel, there is no reaction, but if the spins are oppositely directed, the reaction rate is twice the unpolarized rate.

If the UCN and ^{3}He spin polarization are perpendicular to the applied magnetic field, they will precess at their respective Larmor frequencies, which are the same to within 10% because the gyromagnetic ratios are equal to within 10%. The spin polarizations will oscillate between being parallel and antiparallel, and the scintillation light will be modulated at 10% of the Larmor precession frequency. A change in this frequency with a change in the electric field orientation would be evidence for an nEDM.

Because the ^{3}He-UCN relative precession rate is sensitive to the static magnetic field, our experiment still needs a co-magnetometer. In practice, monitoring the field external to the UCN storage volume does not provide an adequate measure of systematic magnetic fields (e.g., due to leakage currents) seen by the UCN.[1,2] Our current plan is to use SQUID sensors to directly monitor the ^{3}He precession to provide a measurement of the time- and volume-average magnetic field seen by both the ^{3}He atoms and the UCN while they are being stored together. SQUID sensors being studied by P-21 have enough sensitivity to measure the magnetic fields from a functioning brain and therefore will have sufficient sensitivity to detect the magnetic field from the population of precessing ^{3}He atoms as proposed in the EDM experiment. Experiments at LANL have focused on proving that SQUID sensors will perform in the environment of the proposed EDM experiment.[5,6]

The Diffusion of ^{3}He Atoms in Superfluid Helium

For ^{3}He atoms to be effective as a co-magnetometer, they must uniformly sample the UCN storage bottle. We predicted that the diffusion rate should be proportional to the temperature to the inverse-seventh power. Using the scintillation light from the ^{3}He neutron-capture reaction, we were able to perform tomography on a cylindrical cell 50 mm in diameter and 50 mm long. We used the cold neutron beam on flight path 11A (located at the Lujan Center at LANSCE), collimated to a

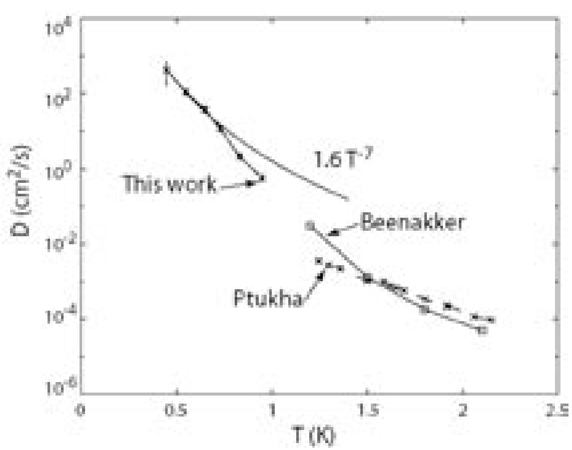


Figure 2. Our experimental results for the diffusion coefficient compared to previous measurements.

diameter of about 2 mm. The cell was mounted on a horizontal dilution refrigerator that could be cooled to 0.3 K. The entire refrigerator/cell cryostat assembly was mounted on a translation apparatus so that it could be moved relative to the fixed cold neutron beam. A three-dimensional rendering of the apparatus is shown in Figure 1. The integrated ^{3}He concentration along a path through the cell was determined by the scintillation rate. The subpanels in Figure 1(a) through (d) show the effects when a heater located near the side of the cell is turned on; the ^{3}He becomes more concentrated at the refrigerated end of the cell.

The results of our experimental measurements of the diffusion coefficient are shown in Figure 2. Our technique allowed extending the measurements from the previous lower limit of 1.2 K to a new lower limit of 0.4 K. Most importantly, we verified that the ^{3}He distribution is uniform (in the absence of a heat flux) and that the diffusion coefficient follows the T^{-7} prediction at temperatures below 0.7 K. These results were published along with an accompanying paper that provides a theoretical analysis of our results.[7]

Conclusion

We are developing a new experiment at LANL to improve the limit of the nEDM by over two orders of magnitude, and we expect to be producing data by 2008. Such an improved limit is crucial to our understanding of T asymmetry in fundamental interactions and has broad applications from elementary particle physics to our understanding of the matter-antimatter asymmetry in the universe.

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